FINAL REPORT

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STUDIES OF FLARES AND DISAPPEARING MAGNETIC FLUX

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STUDIES OF SOLAR FLARES AND DISAPPEARING MAGNETIC FLUX

1. SUMMARY

The following major research accomplishments resulted from Contract N00014-86-K-0139:

(1) The first research paper devoted entirely to the topic of 'flaring arches' were initiated and completed by S.F. Martin and collaborator Z. Svestka. A second paper is in progress.

(2) A collaborative paper on 'Anomalously Dense Flare Loops' was published.

(3) The footpoints of the 'giant arches' previously discovered by Z. Svestka were found in Hα observations from the Big Bear Solar Observatory and the Udaipur Solar Observatory. A research paper is being completed by S.F. Martin, Z. Svestka, A. Bhatnagar and G. Poletto.

(4) Several sets of new observations showing a relationship between cancelling magnetic fields and flares were acquired and analyzed. A research paper is in progress by S.H.B. Livi.

(5) A new hypothesis is advanced that cancelling magnetic fields are necessary condition for the energy build-up to solar flares.

Below we elaborate on the significance of these research results and give the status of the related publications.

1. FLARING ARCHES

1.1.1 Summary of "FLARING ARCHES I - Major Events of 1980 November 6 and 12" by Sara F. Martin and Zdenek Svestka

Flaring arches are a newly recognized high energy component of some solar flares. The arches have been detected in the corona in X-rays and in Hα images. X-ray and Hα emission appear to flow into the corona from the primary footpoint in a flare and both follow the same arch-shaped trajectory to their destination at a secondary footpoint at a distant point in the same active region. The X-Ray component precedes the majority of the Hα.

It is convenient to describe the flaring arch events as having four phases: (1) an early phase indicated by the a brightening of the the secondary footpoint in Hα which we deduce to be caused by the propagation of a low density of undetected electrons through the arch (2) a second phase characterized by X-ray emission propagating through the arch and additional brightening of the secondary footpoint in Hα and X-rays, and (3) a third phase characterized by the flow of Hα emitting

mass through the arch but with no additional brightening of the secondary footpoint and (4) an aftermath when low intensity Hα and/or soft X-rays propagate in the re.verse direction through the arch.

The overall physical picture within the arches is that, at any given cross-section, there is an increase in density with time; the events start with low densities, of the order of 10^9, during the early phase, increase to at least 10^{10} during the X-ray phase and further increase to at least 5×10^{11} particles cm^{-1} during the maximum Hα phase near the end of the event. During the X-ray phase there is a density gradient within the arch which increases from about 10^{10} at the secondary footpoint to 10^{11} at the primary footpoint.

The overall temperature structure of the arch is the inverse of the density structure: the early phase (corresponding to the early Hα brightening of the secondary footpoint) is clearly non-thermal; the X-ray phase corresponds to temperatures of greater than 20×10^6 K. During the late Hα phase the temperature drops to about 10^4 K.

From the speeds of propagation derived from the X-ray and Ha components, we see that the propagation of the various components through the arch follows the temperature pattern: the highest speeds are in the electron streams at the start of the event; at least two velocity components with intermediate speeds are found for the X-ray phase (400-1900 km s^{-1}) and low speeds (less than 400 km s^{-1}) characterize the Hα phase near the end of the event. In the L arch, there is also a low speed (238 km s^{-1}) injection of Hα emitting mass at the start of the event.

The injection of mass into the flaring arches and the propagation of X-rays along the arch are subjects that offer new challenges to the modelling of this component of some flares.

1.1.2 Summary of "FLARING ARCHES II - Events in the Arch System of 6/7 November 1980" by Zdenek F. Svestka, Frantisek Farnik, Juan M. Foltenla, and Sara F. Martin

The two major events of flaring arches discussed in Paper I (on 6 and 12 November 1980) occurred in configurations that persisted in the active region for several days. Many weaker events, some very similar to the major arches and others with different characteristics, appeared repeatedly in these two structures. In this paper we have described and analyzed the activity that was associated with the arch structure of November 6 (which produced the SB arch of Paper I).

The area that can be identified with the primary footpoint of the flaring arches on 6 and 7 November became first visible in X-rays at about 08 UT on 6 November. Since 10:00 UT this site was the source of 13 quasi-periodic brightenings described and analyzed by Svestka et al. (1982, 1983). Though this emission was confined to the primary footpoint, the existence of an arch-like connection and its secondary footpoint began to be indicated after 11:20 UT. At 14:44 UT, the full arch gradually began to brighten in X-rays during the onset phase of a major dynamic flare.

During the decay of this flare, the first flaring arch was observed in Hα at the Big Bear Solar Observatory early in the morning of 6 November. Seventeen

such events were recognized before midnight UT and several more on 7 November. The quasi-periodicity of about 19 min., well-defined during the occurrence of the quasiperiodic variations, seems to be partly maintained in the occurrence of the flaring arches as well.

In addition to the SB arch of Paper I, we have analyzed three other events of this series of flaring arches. for which we have good HXIS data in X-rays. All these events exhibit characteristics quite similar to those found earlier for the bright SB arch. in particular: typical steep X-ray bursts, fast enhancement of secondary footpoints in Hα and delayed brightening in X-rays, a harder X-ray spectrum at the secondary footpoints, and delayed 'flow' of Hα emission through the arches. Thus observations of these other events demonstrate that the 'flaring arch' is a distinct solar phenominon with specific characteristic properties.

We have then compared, for the brightest SB arch, the Hα data from Big Bear, O V data from UVSP, X-ray data from HXIS, in an effort to getmore information about physical properties of the flaring arches. Under the aassumption (taken from Rust, Simnett, and Smith, 1985) that the X-ray emission, moving through the arch, is excited by a conduction front, we have obtained the following results:

An instability at the primary footpoint of the arch, marked by the steeply rising hard X-ray burst, first accelerates electrons which propagate through the least dense loops of the arch system (density of the order of 10^9 cm^{-3} and excite Hα emission at the secondary footpoint. At about the same time plasma is injected into the arch system, giving rise to more and less dense arch components.

The head of the ejection creates a thermal front which gives rise to the observed X-ray emission. It propagates (in various components) with a top speed of about 2000 km s^{-1} and mean speed of ~1000 km s^{-1}. Immediately behind the front, the plasma temperature is close to 2×10^7 K and the density decreases from about 10^{11} cm^{-3} at the primary, to ~3×10^{10} cm^{-3} at the secondary footpoint as the temperature scale height of the propagating front increases.

The bulk of the ejected plasma moves farther behind the front, with lower temperature, higher density (about 10^{10} cm^{-3} at the primary, and ~10^{11}cm^{-3} at the secondary footpoint), and slower speed that decreases from > 600 km s^{-1} near the primary, to about 80 km s^{-1} near the secondary footpoint. This bulk of the arch plasma is visible in the UVSP O V line emission which puts a lower limit on its temperature: 3×10^6 K.

Lagging still further behind is the plasma flow in the densest parts of the arch system which eventually become visible in emission in the Hα line: the speed decreases from > 300 km s^{-1} near the primary, to < 30 km s^{-1} near the secondary footpoint. The density of this rear part of the ejection must be at least 5×10^{11} cm^{-3} at the secondary footpoint (in order to appear in emission in Hα and 7×10^{12} cm^{-3} near the site of the ejection.

The ejection at the primary footpoint also gives rise to shocks which hinder the free propagation of accelerated partcles through the arch. Only after the shock arrival at the secondary footpoint, the particle flow can be fully restored in the parts of the system of arches of lowest density (cf. Paper I). The time of the shock

arrival should not differ much from the arrival of the conduction front. Therefore, during the first 30-60 s (in the SB-type arches) only the Hα excitation is seen at the secondary footpoint. Strong enough bremsstrahlung (much less efficient than Coulomb collisions) must wait for the full stream of electrons after the arrival of the shock front. This flux then causes the observed hardening of the X-ray spectrum at the secondary site.

These results essentially confirm, in a more quantitative way, the qualitative conclusions in Paper I.

1.2 Summary of 'ANOMALOUSLY DENSE FLARE LOOPS' by Z. Svestka, J.M. Fontenla, M.E. Machado, S.F. Martin, D.F. Neidig, and G. Poletto in Solar Physics (1988, Vol. 108, 237-250)

The dynamic flare of 6 Noveber 1980 (max. $\approx$ 15:26 UT) developed a rich system of growing loops which could be followed in Hα observations from the Big Bear Solar Observatory for 1.5 hours. Throughout the flare, these loops, near the limb, were seen in emission against the disk. Theoretical computations of b-values for a hydrogen atom reveal that this requires electron densities in the loops to be close to 10^{12} cm^{-3}. From measured widths of higher Balmer lines the density at the tops of the loops was found to be 4×10^{12} if no non-thermal motions were present.

It is now general knowledge that flare loops are initially observed in X-rays and become visible in Hα only after cooling. For such a high density, a loop would cool through radiation from 10^7 K to 10^4 K within a few minutes so that the dense Hα loops should have heights very close to the heights of the X-ray loops. This, however, contradicts the observations obtained by the HXIS and FCS instruments on board SMM which show the X-ray loops at much higher altitudes than the loops in Hα. Therefore, the density must have been significantly smaller when the loops were formed and the flare loops were apparently both shrinking an becoming denser while cooling.

1.3 FOOTPOINTS OF THE GIANT ARCHES

We have initiated a draft of the paper describing our finding of the faint, long-enduring footpoints of giant X-Ray arches. The 'giant' arches were discovered by Z. Svestka in 1980 data from the Hard X-Ray Imaging Spectrometer flown on board the SMM Satellite. The following subsections summarize the previous observations of giant arches, describe how we were able to identify the footpoints, and give some of the implications of this finding.

1.3.1 Summary of the Properties of Giant Arches

Giant arches overlying active regions were discovered by Svestka et al. (1982a,b) in data from the Hard X-Ray Imaging Spectrometer (HXIS) operated on board the Solar Maximum Mission (SMM). Seven examples of giant arches have been found to date in HXIS data obtained in 1980 (cf. Hick 1988); five of these

occurred in a homologous series; another four giant arches have been found in Flat Crystal Spectrometer (FCS) images (Hick et al. 1988). From the homologous series, it has been deduced that the giant arches are long-lived enhancements within pre-existing coronal structures. Although they last for many hours, their initial enhancements, in 10 of the eleven known events, have coincided with beginning of major dynamic (two-ribbon) flares in the active regions above which the arches develop. The giant arches have a length scale and altitude of approximately 10^5 km or more. They continue to brighten during the decay of the initiating flares and persist for many hours after the associated flares are no longer visible in Hα. Previous studies have not uncovered any other specific association of the giant arches with other active region structures or events. The arches can best be seen in HXIS data by integrating successive HXIS images in the lowest energy channel (3.5–5.5 keV) over time intervals of several to tens of minutes.

1.3.2 The First Identification of Giant Arch Footpoints

While studying one of the initiating Hα flares of a giant arch and a series of subsequent flaring arches observed on 6 November 1980, we noted the existence of a long-lived plage enhancement in an area of single polarity adjacent to the the active region that produced these flares. The plage did not have any obvious connection with the active region more to the west. It began to brighten about 15:30 UT and reached maximum brightness close to the time of the maximum X-ray brightness in the arch. Thereafter the plage was decaying and returned to its original brightness at about 23 UT. This plage enhancement had escaped detection in previous viewings of the Hα time lapse films from the Big Bear Solar Observatory because of its very slow evolution and low contrast relative to the many other structures.

Using a simple photometer, we made a light curve of the brightest part of the plage which gradually shifted in position. From this light curve, we found that the plage brightening had a time history in common with the giant X-ray arch; both began to brighten at about 15 UT and persisted throughout the rest of that day. Because of this close correspondence in time and relative brightness, we suspected that the plage brightening might be footpoints of the eastern system of legs of the giant arch. If so, we thought that we should be able to find another subtle plage enhancement that would correspond to the other foot of the giant arch. We searched for another slow brightening in and around the active region but found none. Instead, we could only identify numerous discrete flares.

Because the giant arches begin concurrently with major two-ribbon flares, the other alternative is that the other unidentified foot of the giant arch is adjacent to or coincides with one of the chromospheric flare ribbons. More specifically, it would be the ribbon lying over photospheric magnetic field opposite in polarity from the magnetic field at the site of the enhanced plage. In this configuration the footpoints are scattered along the western "ribbon" of the active region; thus we suppose that in the east the footpoints are relatively more concentrated, in the plage mentioned above, than the western footpoints which could be scattered over the length of the flare ribbon to the west of the inversion line. The distance between the footpoints

would be then approximately 180 Mm which is comparable to the altitude of the arch. Various areas along the western ribbon intermittently brightened and decayed all the time, and these brightenings might well have been the footpoints of different elements of the arch.

There is also another posibility that the western footpoints of the giant arch were concentrated in a small area near the big leading spot which was the seat of the growing loop system of the dynamic flare discussed in Section 2.

1.3.3 The Identification of Additional Events

If the plage enhancement is truly related to the giant arch in the manner depicted in Figure 3, then we thought we should be able to find other plage enhancements with other giant arches. Without referring to the published records of other giant arches, we searched the time-lapse films at the Big Bear and Udaipur Solar Observatories for other plage enhancements in the same plage during the interval from 6 through 13 November and found four additional events. Then we checked the published record on giant arches during this interval and found that each of the additional plage events corresponded in time with the occurrence of a known giant arch. Furthermore, there were no other known giant arches without corresponding plage events. These findings are not necessarily evidence that our suggested configuration is correct, but they are confirmation of a physical connection between the plage enhancements and the giant arch events. Additionally, we had discovered a means of identifying giant arches from time-lapse Hα images.

1.3.4 Properties of the Footpoints of Giant Arches

From our analyses of the plage enhancements listed in Table 1 we can deduce some new information about the physical nature of the associated giant arches that could not be previously known from only low resolution, large-scale X-ray images. The specific sites of the enhancement of the plage vary in location as a function of time. The time-lapse sequences during the events all show similar changes in the spatial distribution of the brightened elements within the plage. From this characteristic we conclude that the plage enhancement as a whole is an envelope of many successively forming an decaying sub-structures. The size of the substructures are at least as small as the spatial resolution allows us to distinguish. The smallest measureabale elements are approximately 1 arc sec in diameter when seen under the best atmospheric imaging conditions. Under worse atmospheric imaging conditions such small elements are not distinguishable. In this respect the plage enhancements are very much like low intensity flares. Spectral and spatial observation have shown that many flares likewise consist of an envelope of successively forming and decaying flare elements (Svestka, Martin and Kopp, 1980, Solar and Interplanetary Dynamics (eds. M. Dryer and E. Tandberg-Hanssen, p. 217). However, in many flare observations, the flare points are indistinguishable due to inadequate spatial resolution.

Assuming that the plage enhancements are at one end of the arch, we can infer that the arch also consists of fine structure that cannot be seen in the HXIS images.

Spatial and temporal changes within the arches were already known. Now, we know that the spatial character and duration of the fine structure within the arch must be related to the size and duration of the successively forming and decaying elements seen in the plage.

1.3.5 Implications of the Finding of Footpoints of the Giant Arches

From our analysis to date, the following consequences can be drawn from the existence of chromospheric footpoints of the giant arches:

(a) Fine structures within the giant arch must be more short-lived- lasting on minutes - and more numerous than present X-Ray observations reveal; conductive cooling must play an important role in the giant arches but it might be partly inhibited in order to keep the arches alive for the long periods observed.

(b) The heating process proposed by Hick and Priest (1988) must be modified by taking into account the long duration of the chromospheric heating.

(c) The dynamic flares that cause arch revivals cannot be associated with mass ejections, or the mass ejection must be non-classical (i.e. no filament eruption) like in the arch event of 21 May 1980 (McCabe et al., 1986).

(d) If there is a (classical) mass ejection associated with a dynamic flare and thereafter a giant arch is seen, this arch must have been formed after the ejected mass got detached from the surface magnetic fields.

1.4 CANCELLING MAGNETIC FIELDS

When opposite polarity magnetic features move into apparent juxtaposition, both polarities begin to disappear at their common interface. This type of disappearance of magnetic flux is described by the observational term "cancellation" (Livi, Wang and Martin 1985; Martin, Livi and Wang 1985). At present there are several possible interpretations of cancellation. Several authors have suggested that the cancelling fields should be interpreted as submergence. Zwaan (1987), however points out the difficulty of differentiating between simple submergence and extraction or submergence of magnetic flux in association with magnetic reconnection. Until we are able to unambiguously interpret how magnetic flux disappears from the solar photosphere we choose to continue using the observational term 'cancellation'.

Cancellation sites on the sun are important because they are the same sites where filaments form and erupt and above which solar flares occur. Conversely, the presence of filaments and the ocurrence of flares at cancellation sites are both significant to the physical interpretation of cancellation. These associations provide strong evidence that cancellation cannot be interpreted as simple submergence.

The development of the sheared configuration and the formation of filaments at cancellations sites is evidence that some of the line of sight component is being reconfigured into the transverse component. Thus at least part of the apparent

disappearance of magnetic flux is not representing disappearance of the total field but rather a changing geometry and probably an increase in the transverse component of the field. The formation of filaments is a clue that the magnetic field is possibly being reconnected at the photosphere or in the chromosphere but in either case, below the height of very low filaments. If this hypothesized reconnection takes place at the photosphere, cancellation would be interpreted as flux being pulled out of the photosphere or expelled from the photosphere. If the supposed reconnection takes place in the chromosphere, then cancellation can be interpreted as the submergence of flux in association with reconnection which also results in a concurrent reconfiguration of the field in the chromosphere and corona (Zwaan 1987).

Of the three interpretations of flux disappearance outlined by Zwaan (1987), the case of simple submergence seems to be ruled out. If the fields were simply submerging, one would not expect sheared magnetic configurations or the formation of filaments which are indicative of sheared configurations. Additionally, the occurrence of flares at cancellation sites suggests that an energy build-up occurs in association with cancellation rather than an energy loss which simple submergence would imply.

1.5 THE RELATIONSHIP OF CANCELLING MAGNETIC FIELDS TO FLARES

We are continueing a detailed study of the association of flares to cancelling magnetic fields using several sets of new magnetic field data and Hα filtergrams recorded at the Big Bear Solar Observatory.

In addition to our analyses of new data, a review paper on the "Association of Flares to Cancelling Magnetic Fields on the Sun" is being prepared. This paper was presented at IAU Colloquium 104 on 'Solar and Stellar Flares' held at Stanford University from 15-19 August 1988. The author of this paper is Silvia H.B. Livi.

To date, we have found no examples of flares that do not begin over or adjacent to cancellation sites or where cancellation is inferred. However, parts of large flares are seen to spread into fields that are not cancelling. In addition, cancellation is a slow process relative to the time scale of flares. We have not yet been able to identify any particular time that is unique to the occurrence of a given flare. But is should be emphasized that these studies are still in an early stage and many aspects of magnetic field remain to be investigated.

From the close spatial association of cancellation sites to the initiation sites of solar flares, along with the lack of concurrent and unique temporal change in the magnetic field at the times of flares, we conclude that the association between cancelling fields and flares is indirect rather than direct. We envision cancellation as part of the flare build-up process rather than the trigger of flares.

It has been known for a long time that flares occur at the same sites where filaments have formed. It is also well known that filaments coincide with zones where the magnetic field in the photosphere and chromosphere is strongly sheared. The sites of sheared magnetic fields are also now recognized to coincide with or

lie below the sites of flares. Recent studies (Martin 1986; Hermans and Martin 1986) have further shown that the sheared configuration, as revealed by filaments in the chromosphere, develops in conjunction with cancelling magnetic fields in the photosphere. Since filaments only form when maximum shear is established and flares occur only after a filament (or maximum shear) has developed, we deduce that cancellation is a precondition for flares. Because we have not yet found flares at sites without observed or inferred cancellation, we advance the following new hypothesis: CANCELLING MAGNETIC FIELDS ARE A NECESSARY PRECONDITION FOR THE OCCURRENCE OF SOLAR FLARES.

If our hypothesis is true, there is renewed hope for a major advancement in the field of flare forecasting. More detailed studies of the association of cancelling fields are highly recommended as a test of this hypothesis.

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2. INDEX OF REPORTS

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2.2 Publications/ Patents/ Presentations/ Honors Report, August 1987

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3. INDEX OF PUBLICATIONS

3.1 Papers submitted or published in refereed journals

"A Dynamic Flare with Anomalously Dense Loops" Svestka, Z., Fontenla, J.M., Machado, M.E., Martin, S.F., Neidig, D.F., and Poletto, G.: 1987, Solar Phys. 108, 237.

"Flaring Arches I" Martin, S.F. and Z. Svestka Z.: 1988, Accepted by Solar Phys.

"Flaring Arches II " Svestka, Z., Martin, S.F., and Farnik, F.: 1988, Submitted to Solar Phys.

3.2 Papers in Progress

"The Footpoints of Giant Arches" Martin, S.F., Svestka, Z.F. and Bhatnagar, A.

"The Relationship of Flares to Cancelling Magnetic Fields" Livi, S.H.B.